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Enhancing Efficiency in Wireless Power Transfer in Electric Vehicles through Optimization Strategies

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***Abstract*—The rise of electric vehicles (EVs) has spurred interest by implementing efficient and convenient charging methods. Wireless Energy Transmission technology presents a promising avenue for overcoming the constraints of conventional wired charging systems. This survey paper systematically assesses the current status of WPT with mutual coupling, exploring existing landscape and future prospects, particularly in enhancing charging efficiency for EVs. By examining recent research developments, addressing associated challenges and opportunities, and scrutinizing parameters such as alignment optimization, coil design, and system integration, this paper delves into the key factors that impact efficiency improvements in wireless power transfer for electric vehicles, offering a thorough analysis to guide development efforts. Through its advocacy for continued exploration and innovation, this survey paper endeavors to drive progress in the evolving system of Wireless Energy Transmission, thereby facilitating the broader adoption of efficient and user-friendly wireless charging solutions in the context of electric vehicles.**

***Index Terms*— Electric Vehicles (EVs), Wireless Power Transfer (WPT).**

I. INTRODUCTION

The imperative for sustainable transportation underscores the function of electric vehicles in transportation in mitigating climate change and reducing reliance on finite fossil fuels. The increasing demand for EVs accentuates necessity for innovative charging technologies that enhance convenience and surmount challenges posed by conventional wired systems. Wireless Power Transfer (WPT) technologies, particularly magnetic resonance-based approaches, have emerged as promising solutions, offering enhanced usability and acceptance of EVs by providing greater charging pad flexibility, eliminating alignment constraints, and boosting overall power transfer efficiency. This paper is dedicated to integrating magnetic resonance-based WPT to maximize charging efficiency while addressing design, safety, and environmental considerations. Its objective is to significantly enhance the improvement of a reliable and widespread wireless charging ecosystem for EVs, where magnetic fields efficiently transmit energy across an air gap, seamlessly connecting the charging infrastructure with EVs. This research holds profound significance in potentially revolutionizing EV charging, transcending limitations of traditional methods, and facilitating a more convenient and widespread adoption of EVs. With the accelerating electrification of the automotive industry, the significance of efficient wireless charging solutions becomes paramount for the success and sustainability of electric transportation.

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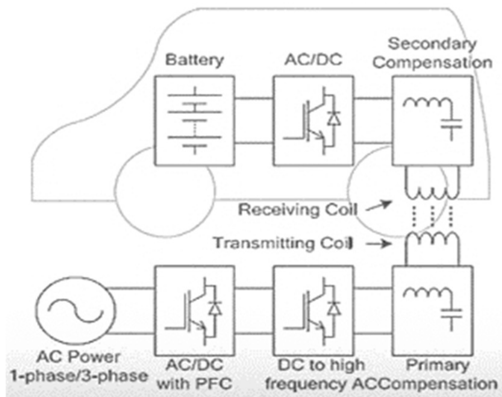
This paper outlines the methodology, design considerations, challenges, and prospective solutions for implementing magnetic resonance-based WPT for EVs, thereby advancing EV charging infrastructure.

II. WIRELESS ENERGY TRANSMISSION

Magnetic resonance-based Wireless Energy Transmission offers a trans-formative solution, eliminating the inconvenience of tangled wires and providing a seamless and efficient power delivery mechanism. Recent technological progress has amplified the appeal of WPT, particularly in Electric Vehicle (EV) wireless charging applications, where it presents a convenient and effective means of powering EVs without the limitations of physical connectors. The charging process commences with the conversion of incoming AC utility power into stable DC via a power factor corrected AC-to-DC converter. Subsequently, the system converts the DC input power to high-frequency AC, which then energizes the transmitting coil via a compensation network, thereby optimizing Wireless Energy Transmission efficiency in EV charging systems. The AC voltage induced in the receiving coil by the high-frequency current in the transmitter is then rectified to usable DC power, completing the Wireless Energy Transmission process.



III. MUTUAL COUPLING

Resonant Wireless Energy Transmission systems rely on diverse compensation topologies such as series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP) networks, each offering distinct advantages and trade-offs crucial for optimizing power transfer efficiency. Modeling such systems involves representing coupled power transfer coils as coupled inductors, simplifying the analysis and comprehension of the system's dynamic interactions and behaviors.

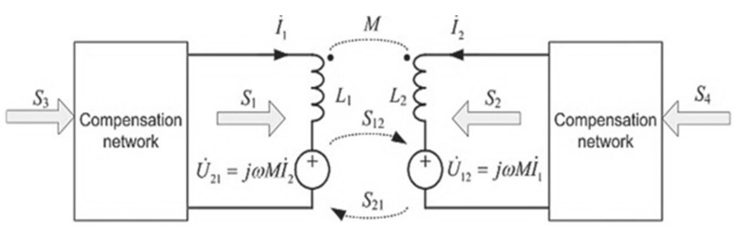


Figure 2 Mutual Coupling for resonant wireless transmission

Within the Wireless Energy Transmission system, the symbol L1 represents the inductance of the power-generating coil, while L2 represents the inductance of the receiving coil. Similarly, S1 and S2 indicate the amount of power entering the transmitting and receiving coils, respectively, providing a clear picture of power flows within the system. S3 and S4 represent the power delivered by the converter. S3 indicates the power coming from the source and entering the transmitting coil, while S4 shows the power transferred from the receiving coil back to the system in the wireless energy transmission system. Moreover, the symbols S12 and S21 are utilized to represent the power interchange between the power transfer coil. These parameters elucidate the mutual power flow and transfer efficiency within the wireless energy transmission system, providing a comprehensive understanding of the energy exchange dynamics between the power transfer coils.

IV. METHODOLOGY

Figure 3 depicts the ongoing investigation into the Wireless charging with magnetic fields system, segmented into two primary sections. The external component, situated outside the vehicle, comprises ahigh-frequency DC/AC full-bridge inverter, a transmission coil (L1), and compensation capacitance (C1). Conversely, the internal section within the vehicle integrates a resonant tank circuit, formed by the reception coil (L2) and compensation capacitance (C2), to facilitate effective inductive power transfer. Command of the system is managed on power transfer coil. The secondary buck-boost converter is tasked with maintaining appropriate voltage and current levels for battery charging. Concurrently, the primary inverter utilizes a perturb and observe algorithm to dynamically track the optimum efficiency transmission point, thereby optimizing the overall performance of the inductive power transfer system.

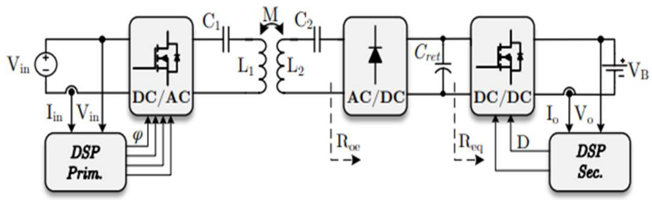


Figure 3 Wireless charging with magnetic fields system

The design methodology hinges on utilizing the steady-state analytical equations of the circuit, necessitating the adoption of a simplified circuit model to facilitate analysis and design. This simplification is achieved by implementing a first harmonic approximation. By employing this approximation, the input inverter is replaced with an alternating voltage source set at the resonant frequency. Similarly, the battery, output rectification, and buck-boost converter are substituted with an equivalent resistive load, representing a particular operational state. The result of this simplification is depicted in Figure 2, offering a clearer depiction of the circuit within this specific analytical framework.

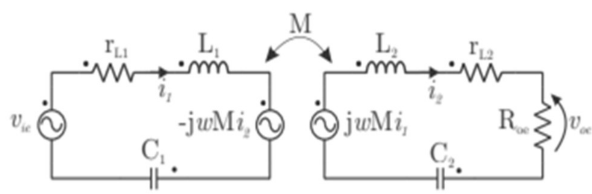


Figure 4 Sin reference function, windowed with a raised cosine window

In Figure 4, r_{L1}, r_{L2}, and R_{oe} represent, respectively, the resistance of the primary coil**,** Considering both the resistance of the receiving coil and the circuit's equivalent load resistance is crucial for optimization. The voltage v_{ie} represents the amplitude of the first harmonic synthesized by the inverter. The relationship between the phase angle of the arms (φ) and v_{ie} can be determined as

$$v_{ie} = \frac{1}{2\sin^{-1}\left(\frac{\pi\sqrt{2}}{4\varphi V_{in}}\right)}. \quad (1)$$

The equivalent output resistance (R_{oe}) can be found using the static gain of the buck-boost converter, where the resistance reflected at the converter input (R_{eq}) is expressed by

$$R_{eq} = \left(\frac{1-D}{D}\right)^2 R_o \quad (2)$$

where R_o represents the equivalent resistance of the battery determined using power and voltage measurements at a specific operating point, and D is the duty-cycle of buck-boost converter. Considering the Fundamental Harmonic approximation (FHA), the equivalent Roe could be express as

$$R_{oe} = \frac{8}{\pi^2} R_{eq}. \quad (3)$$

In compensation topologies for Wireless charging with magnetic fields system, two distinct design approaches can be implemented. Efficiency can be improved by either tuning capacitors to resonate with leakage inductances (method 1) or self-inductances of the coils. A comparative assessment of these techniques reveals that compensation through self-inductance demonstrates superior efficiency and increased robustness in handling variations in coil misalignment. Consequently, for our analysis, we have opted for capacitors C1 and C2 to operate in resonance with self-inductances L1 and L2, respectively. This decision permits the calculation and integration of capacitances into the circuit's design utilizing the equations provided. In this manner , at the operating frequency ω0, primary and secondary reactance are nullify each other, so that:

$$C_1 = \frac{1}{\omega^2 L_1} \qquad C_2, = \frac{1}{\omega^2 L_2} \tag{4}$$

$$1/j\omega_0 C_1 = j\omega_0 L_1 \quad , \quad 1/j\omega_0 C_2 = j\omega_0 L_2. \tag{5}$$

The phasor are the rms values of the sinusoidal voltages and currents, defined by:

$$\begin{aligned} v_{ie} &= \mathrm{V}_{ie}\sqrt{2}sin(\omega t) \\ i_1 &= \mathrm{I}_1\sqrt{2}sin(\omega t + \theta_1) \\ v_o &= \mathrm{V}_o\sqrt{2}sin(\omega t + \theta_2) \\ i_2 &= \mathrm{I}_2\sqrt{2}sin(\omega t + \theta_2) \end{aligned} \tag{6}$$

Using Kirchhoff Law, it is possible to write the primary current (I_1) and secondary current (I_2) as

$$\mathrm{I}_1 = \frac{V_{ie}(r_{L2} + R_{oe})}{\omega^2 M^2 + r_{L1}(r_{L2} + R_{oe})}, \tag{7}$$

$$\mathrm{I}_2 = \frac{V_{ie}(j\omega M)}{\omega^2 M^2 + r_{L1}r_{L2} + R_{oe}r_{L1}}. \tag{8}$$

Multiplying 8 by the load resistance Ro yeilds the output voltage, represented by

$$\mathrm{V}_o = \frac{V_{ie}(j\omega M)R_{oe}}{\omega^2 M^2 + r_{L1}r_{L2} + R_{oe}r_{L1}} \tag{9}$$

Multiplying (8) by the 8 by Equation 9 results in the following expression for power output

$$P_o = \frac{{V_{ie}}^2 \omega^2 M^2 R_{oe}}{[\omega^2 M^2 + r_{L1}r_{L2} + R_{oe}r_{L1}]^2}. \tag{10}$$

The apparent input power is calculated by multiplying the rms value of the input voltage V_{ie} by the modulus of 7, and it can be represented by**:**

$$S_{in} = \frac{{V_{ie}}^2(r_{L2} + R_{oe})}{\omega^2 M^2 + r_{L1}(r_{L2} + R_{oe})}. \tag{11}$$

The input power is given by:

$$P_{in} = \frac{{V_{ie}}^2(r_{L2} + R_{oe})}{\omega^2 M^2 + r_{L1}(r_{L2} + R_{oe})}. \tag{12}$$

Hence, the circuit efficiency can be derived from 10 and 12, and this can be given by:

$$\eta = \frac{R_{oe}}{\left[1 + \frac{r_{L1}(r_{L2}+R_{oe})}{\omega^2 M^2}\right](r_{L1} + r_{L2})}. \tag{13}$$

V. RESULTS AND DISCUSSION

The simulation involves multiple subsystems, initiating with the rectification and inversion of grid power before its application to the primary coil. After undergoing an additional rectification process, the resulting output is acquired from the secondary coil, with a resistance introduced across the secondary rectifier. The AC/DC Rectifier subsystem is configured with a full bridge rectifier, playing a pivotal role, a rectifier circuit rectifies the AC current, transforming it into usable DC power. On one side, the primary rectifier converts grid AC into tailored pulses for the inverter, while on the receiving end, the secondary rectifier transforms the received AC voltage into DC power for the devices.

The DC/AC Inverter subsystem utilizes Insulated Gate Bipolar Transistors (IGBTs) within a full bridge inverter configuration. In this setup, the rectified grid power is directed to the inverter, and the resulting inverted signal is applied across the primary coil. The effective operation of the inverter section relies on the generation of two gate pulses

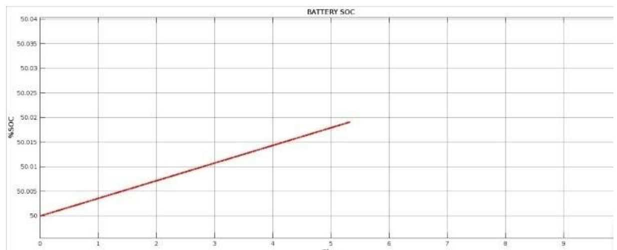


Figure 5 Battery SOC output waveform

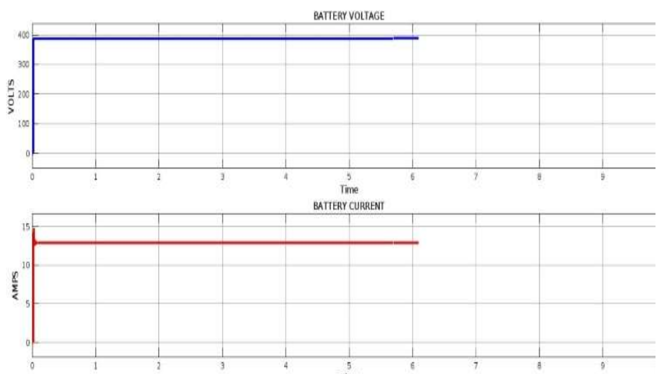


Figure 6 Battery voltage and current output waveform

VI. OPTIMIZING EFFICIENCY

In a Wireless Energy Transmission system, the magnetic couplers serve as essential components, facilitating the efficient transmission of energy without the need for physical connectors or cables. The transmitting side is accurately called the primary coupler, and the receiving side is precisely called the pick-up coupler.

The versatility of magnetic coupler design in a WPT system allows it to be optimized for different EV charging scenarios, like in-ground or in-wheel applications.

Depending on the intended use case, the magnetic coupler can be engineered as either a convenient charging pad or an integrated embedded track, offering flexibility and versatility in deployment options. Maximizing Both the coupling coefficient (k) and quality factor (Q) are vital parameters for achieving higher efficiency, as they directly influence transfer efficiency and overall system performance, making them crucial considerations in system design and optimization efforts. Increasing the size-to-gap ratio of the coupler enhances the coupling coefficient (k), while using thicker wire and larger ferrite section areas boosts the quality factor (Q). While increasing dimensions and exotic materials can improve efficiency, a more practical approach for WPT systems prioritizes maximizing the coupling coefficient (k) with minimal size and cost. In WPT systems, a common approach to achieving a high Q-factor, which is desirable for efficient energy transfer, involves using higher operating frequencies. This is because Q scales directly with the product of frequency (ω) and inductance (L), divided by resistance (R).

Topology	Rating (W)	Freq (kHz)	Switches	Diodes	HF Transformer	Efficiency (%)
Buck-Boost Converter[32]	100	10	3	2	0	98.2
Z quasi-resonant DC/DC Converter[33]	300	20	8	1	0	91.5
Modified buck-boost Converter[34]	500	50	9	0	0	97.2
Buck-Boost Converter[35]	3,800	25	12	1	0	87.2
Dual Active Bridge Converter[36]	20,000	10	18	0	3	94.8
Dual Active Bridge Converter[37]	5,000	100-220	8	4	1	98.2
Modified Bridgeless Luo converter[38]	850	20	3	3	1	90.8
Full Bridge Converter[39]	500	60	5	6	1	97.5
Full Bridge Converter[40]	10,000	85-337	4	8	2	98.5
Interleaved Boost Converter[41]	-	15.5	4	6	1	-
Full Bridge Converter[42]	11,000	15	7	8	1	98.3
Stacked half-bridge Converter[43]	6,600	500	8	0	1	98.2

Figure 7. Table of different converters and their efficiency

A resonant topology on the primary side acts like a magic tuning fork. It aligns the operating frequency of the power electronics converter with the resonant frequency of the sending coil. This perfect match allows the converter to efficiently generate a high-frequency current, boosting the switching frequency, the overall efficiency of the entire system. For even greater control over the received power, an additional DC-DC converter can be added alongside the rectifier. This tag-team duo efficiently converts the high-frequency AC current from the receiving coil into a stable DC voltage, with the converter providing precise voltage or current regulation on the secondary side as needed.

The primary side converter can be configured as either a voltage source converter or a current source converter, according to the specific design requirements and desired operational characteristics. Due to the requirement of a bulky inductor in current source converters, the primary side converter is a full bridge voltage source resonant converter, offering efficient power transfer without the need for large inductors. If resistances were zero, the efficiency of the transformer would be 100 %. Coil resistances generate joule effect, and this heat has to remain at an acceptable level. Minimizing the Joule losses is then a crucial point while designing WPTs, with respect to efficiency and transferable power. R=Pl/A wire where l is length of the coil, A is area of the wire, p is resistivity of the coil.

To boost the efficiency of coupling, a DC/DC converter must be connected on the secondary side to regulate the rectified AC power and efficiently charge the battery.

Recent advancements in electronic power technologies, magnetic coil design, and dynamic charging control have significantly enhanced the systems, providing increased energy efficiency and reliability. The system integrates magnetically coupled power transfer coils with power electronic devices like rectifiers, inverters, and boost converters, all governed by their respective control mechanisms. Resonance operation is utilized to amplify the energy transferred connecting power transfer coils enhancing overall efficiency and effectiveness.

In high-power applications, losses in the coupling zone can limit the power provided despite employing a typical switching frequency for efficient operation. Leakage inductance between the coils in a system hinders power transfer efficiency. This issue can be addressed by implementing reactive current compensation techniques, thereby minimizing the negative influence of leakage inductance. In hard-switched converters, a compensation capacitor enhances power transfer capability and efficiency while mitigating the need for proportionally increasing power capacity with rising switching frequency. Using a resonant topology becomes advantageous, beyond a power-dependent threshold, resonant topologies become increasingly beneficial for the converter, allowing it to maintain high efficiency despite the need for higher switching frequencies; for instance, it's typically below 100 kHz for 500W outputs and decreases further as output power increases. Above the threshold, employing a resonant topology leads to relatively higher efficiency compared to using a hard-switched converter configuration. Additionally, the higher switching frequency enables the utilization of smaller energy storage components, leading to enhanced power density and decreased energy dissipation within the system.

In resonant converters, a precisely timed switching voltage is applied to a resonant tank circuit, inducing a sinusoidal current flow. As a result, the semiconductor switches in the resonant converter are triggered to turn on or off at points of zero voltage or zero current, minimizing switching losses and enhancing overall efficiency.

VII. Conclusion

The investigation into wireless energy transmission with mutual coupling marks a significant stride in addressing the imperative for efficient and user-friendly charging solutions for electric vehicles (EVs). This comprehensive paper delves into the current state of WPT technology, with a specific focus on magnetic resonance-based systems, which promise notable advancements over conventional wired charging infrastructure. By investigating the intricacies of mutual coupling, alignment optimization, coil design, and system integration, through its analysis, this paper provides valuable understanding of the factors that shape the efficiency of wireless charging for EVs. It becomes evident that resonance operation emerges as a critical factor for maximizing power transfer efficiency and minimizing losses in wireless EV charging. The methodology outlined in this study provides a structured approach to implementing magnetic resonance-based WPT systems, emphasizing the significance of control algorithms and circuit optimization techniques. Through dynamic tracking of maximum efficiency transmission points and employing simplified circuit models, researchers can refine the configuration process and expedite the optimization of reliable and efficient wireless charging ecosystems. Leveraging resonant topologies and higher switching frequencies enables researchers to mitigate power losses and improve overall system efficiency, thereby facilitating high-performance wireless charging solutions. In conclusion, this survey paper consolidates recent research developments and identifies future opportunities for innovation in WPT for EVs. By fostering ongoing exploration and collaboration, the insights presented here aim to drive advancements in wireless charging technology, ultimately accelerating the widespread acceptance and adoption of electric vehicles within a sustainable transportation framework.

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